Multiple and single measurements of a mesoscopic quantum system with two permitted states

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Mesoscopic loop is proposed in many works as possible solid-state quantum bit, i.e. two-state quantum system. The quantum oscillations of resistance and of rectified voltage observed on asymmetric superconducting loops give evidence of the two states at magnetic flux divisible by half of the flux quantum. But our measurements of quantum oscillations of the critical current of these loops have given results coming into irreconcilable contradictions with result of the observations of the quantum oscillations of resistance.

Introduction

One of the most intriguing problems of mesoscopic physics is possibility of quantum superposition of macroscopic states. It is especially urgent because of the aspiration for realization of the idea of the quantum computation [1]. Ambiguous experiments [2] can not be considered as an evidence of the macroscopic quantum superposition and possibility of solid-state qubit because of the obvious contradiction between quantum mechanics and macroscopic realism [3]. Quantum superposition presupposes that single measurement should give result corresponding to one of the permitted states whereas multiple measurement should give a result corresponding to an average value. We present experimental results corresponding such measurements.

1. SUPERCONDUCTING LOOP AS POSSIBLE QUANTUM BIT

Superconducting loop interrupted by one or several Josephson junctions is proposed in many publications [4] as possible quantum bit, i.e. a two-state quantum system which can be used as main element of quantum computer. This proposal is based on the assumption on two permitted state in such loop with half quantum $\Phi_0 = \pi\hbar/e$ of magnetic flux $\Phi = (n + 0.5)\Phi_0$. The authors [4] do not doubt that the two states exist and any observation will find a value corresponding to one of them. But nobody must be sure of anything in the quantum world till unambiguous experimental evidence. A. Einstein, B. Podolsky, and N. Rosen were sure [5] that a process of measurement carried out on a one system can not affect other system in any way. But experimental results [6] have shown that it can and this phenomenon is called now Einstein - Podolsky- Rosen correlation.

The numerous observation of the Little-Parks oscillations [7] of resistance $\Delta R(\Phi/\Phi_0)$ of superconducting loop [8] prove quantization of velocity circulation $\oint_l dlv = (2\pi\hbar/m)(n - \Phi/\Phi_0)$ of superconducting pairs and that the permitted state with minimum energy has overwhelming probability even at $T \approx T_c$. The maximum $\Delta R(\Phi/\Phi_0) \propto \overline{v^2}$ [9] and zero value of the rectified voltage, corresponding to the average velocity $V_{dc}(\Phi/\Phi_0) \propto \overline{v}$ [10], observed at $\Phi = (n+0.5)\Phi_0$ may be considered as an experimental evidence of two permitted states with the same minimum energy $\propto v^2 \propto (n - \Phi/\Phi_0)^2 = (1/2)^2$ and $(-1/2)^2$: $\overline{v^2} \propto (1/2)^2 + (-1/2)^2 = 1/2$ whereas $\overline{v} \propto (1/2) + (-1/2) = 0$. But it is needed to verify that a single measurement gives a result corresponding $v \propto 1/2$ or $v \propto -1/2$ state.

2. MULTIPLE AND SINGLE MEASUREMENTS OF THE PERSISTENT CURRENT

The measurement of the critical current of an asymmetric superconducting loop, Fig.1, can be used for this verification. The current density equal $j_n = I_{ext}/(s_n + s_w) \pm I_p/s_n$, $j_w = I_{ext}/(s_n + s_w) \mp I_p/s_w$ in the loop halves because of the velocity quantization should mount the critical value, $j_n = j_c$ or $j_w = j_c$, at the external current $I_{c+}, I_{c-} = |I_{ext}| = j_c(s_n + s_w) - |I_p|(s_n + s_w)/s_n$ or $I_{c+}, I_{c-} = |I_{ext}| = j_c(s_n + s_w) - |I_p|(s_n + s_w)/s_w$ depending on the directions of the external current I_{ext} and the persistent current $I_p = 2en_s v = 2en_s[2s_n s_w/(s_n + s_w)](2\pi\hbar/ml)(n - \Phi/\Phi_0)$, Fig.1. One may expect to determine not only value but also direction of the persistent current $I_p = (I_{c-} - I_{c+})(s_w/s_n - s_n/s_w)$ using the critical current I_{c+}, I_{c-} values measured in opposite directions of asymmetric loop with unequal half sections $s_n < s_w$, Fig.1.

Our measurements of aluminum rings with radius $r = 2\mu m$, thickness $d = 40 - 70\ nm$, semi-ring width $w_n = 200\ nm$, $w_w = 400; 300; 250\ nm$ and systems of such rings at $T < 0.99T_c$ have shown that the whole structure jumps from superconducting to normal state at $I = I_{c+}$ or I_{c-}. This means that the ring should remain in superconducting state with the same quantum number n right up to the transition into the normal state and the measurement of $I = I_{c+}$ or I_{c-} should correspond single measurement of the quantum state. One should expect gaps in the $I_{c+}(\Phi/\Phi_0)$, $I_{c-}(\Phi/\Phi_0)$ dependencies and maximum of $|I_p|(\Phi/\Phi_0) \propto |I_{c-} - I_{c+}|(\Phi/\Phi_0)$ at $\Phi = (n + 0.5)\Phi_0$, Fig.1.

We have obtained identical $I_{c+}(\Phi/\Phi_0)$, $I_{c-}(\Phi/\Phi_0)$ dependencies at measurements of four single rings and two

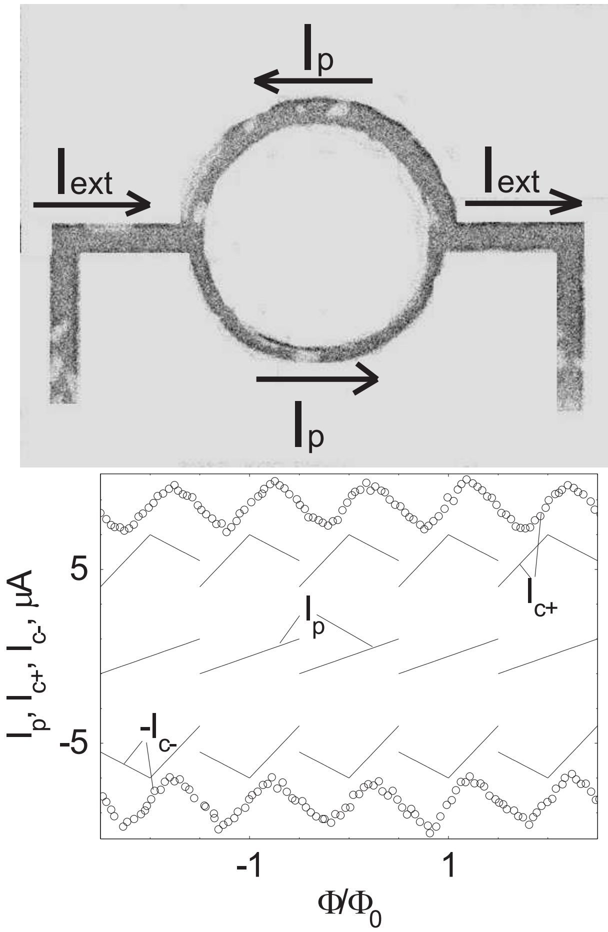

FIG. 1: Photo of the asymmetric Al round loop (ring) with semi-ring width $w_n = 200\ nm$, $w_w = 400\ nm$ and magnetic dependencies of the critical current I_{c+}, I_{c-} expected be observed on such ring at $I_p = 2\ \mu A\ (n - \Phi/\Phi_0)$ and $j_c(s_n + s_w) = 7\ \mu A$. The experimental dependencies $I_{c+}(\Phi/\Phi_0), I_{c-}(\Phi/\Phi_0)$ measured on this ring at $T = 1.225K = 0.99T_c$ are shown also.

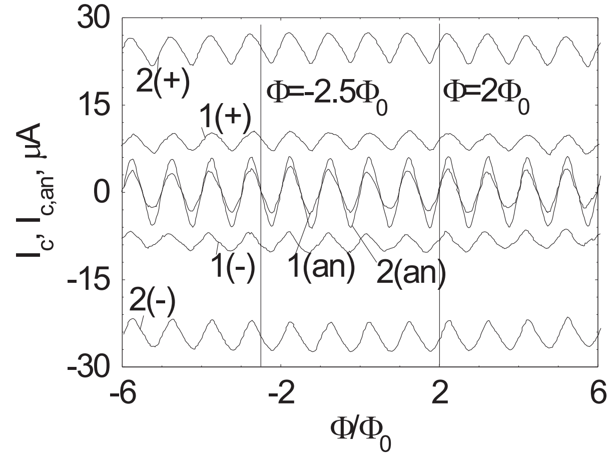

FIG. 2: The quantum oscillations of the critical current I_{c+}, I_{c-} measured in opposite directions and its anisotropy (an) $I_{c,an} = I_{c+} - I_{c-}$ observed on single loops with $w_n = 0.2\ \mu m$, $w_w = 0.3\ \mu m$ and $T_c = 1.23\ K$ at (1) $T = 1.271\ K$ and (2) $1.243\ K$.

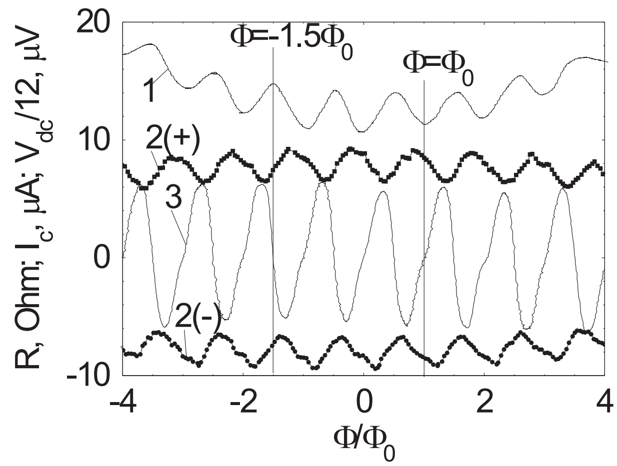

FIG. 3: Magnetic dependencies of (1) the resistance $R - 23\ \Omega$ at T = 1.228 K of (2) the critical current I_{c+}, I_{c-} at T = 1.208 K, and (3) the rectified voltage $V_{dc}/12$, induced by the ac current with frequency f = 0.5 kHz and amplitude $I_0 = 9\ \mu A$ at T = 1.209 K of 20 loops with $w_n = 0.2\ \mu m$, $w_w = 0.4\ \mu m$ and $T_c = 1.23\ K$

systems of identical 20 rings at different temperature, Fig.2,3, which differ from the expected one, Fig.1, in essence. The magnetic dependencies of the anisotropy of the critical current $I_{c,an} = I_{c+} - I_{c-}$, which should be proportional to the persistent current $I_{c,an}(\Phi/\Phi_0) \propto -I_p(\Phi/\Phi_0) \propto -(n - \Phi/\Phi_0)$, cross zero at $\Phi = n\Phi_0$ and $\Phi = (n + 0.5)\Phi_0$, Fig.2, as well as the one of the rectified voltage $V_{dc}(\Phi/\Phi_0) \propto \overline{n} - \Phi/\Phi_0$, Fig.3, corresponding multiple, but not single, measurement of the persistent current states.

It is more strange that the magnetic dependencies of the critical current measured in opposite directions are similar $I_{c+}(\Phi/\Phi_0) = I_{c-}(\Phi/\Phi_0 + \Delta\phi)$ and its anisotropy results from a shift $\Delta\phi = 0.5$ of these dependencies one relatively another. It is very strange that minimum of $I_{c+}(\Phi/\Phi_0)$ and $I_{c-}(\Phi/\Phi_0)$ is observed at $\Phi = (n + 0.25)\Phi_0$ and $\Phi = (n + 0.75)\Phi_0$ but not at $\Phi = (n + 0.5)\Phi_0$ as it should be expected and as it is observed in symmetrical ring [11] since the maximum of the Little-Parks oscillations of asymmetric rings is observed at $\Phi = (n + 0.5)\Phi_0$. We hope that future investigations can clear a nature of this contradictions between results of measurements of $I_{c+}(\Phi/\Phi_0)$, $I_{c-}(\Phi/\Phi_0)$ and $\Delta R(\Phi/\Phi_0)$.

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[1] K. A. Valiev, A. A. Kokin. *Quantum computers: reliance and reality*, Moscow-Izhevsk: R and C Dynamics, 2002 (in Russian); M.A.Nielsen and I.L.Chuang, *Quantum Computation and Quantum Information* Cambridge University Press, 2000; A. M. Steane, *Rept.Prog.Phys.* **61**, 117, 1998;

[2] J. R. Friedman et al., *Nature* **406**, 43, (2000); C. H. van der Wal, A. C. J. ter Haar, *Science* **290**, 773, (2000).

[3] A. J. Leggett and A. Garg *Phys. Rev. Lett.* **54**, 857, (1985).

[4] Y. Makhlin, G. Schoen, and A. Shnirman, *Rev.Mod.Phys.* **73**, 357 (2001); P. Bertet, et al., *Phys. Rev. Lett.* **95**, 257002 (2005); Z. H. Peng, M. J. Zhang, and D. N. Zheng, *Phys. Rev. B* **73**, 020502(R) (2006).

[5] A. Einstein, B. Podolsky, and N. Rosen *Phys. Rev.* **47**, 777 (1935).

[6] A. Aspect, P. Grangier, and G. Roger, *Phys.Rev. Lett* **47** 460, (1981); P. G. Kwiat et al., *idid* **75**, 4337 (1995); G. Weihs et al., *idid* **81**, 5039 (1998); W. Tittel et al., *Phys. Rev. A* **57**, 3229 (1998); J. W. Pan et al., *Nature* **403**, 515 (2000).

[7] W. A. Little and R. D. Parks, *Phys.Rev.Lett.* **9**, 9 (1962).

[8] H. Vloeberghs et al., *Phys. Rev.Lett.* **69**, 1268, 1992.

[9] M. Tinkham, *Introduction to Superconductivity.* McGraw-Hill Book Company (1975).

[10] S. V .Dubonos et al., *Pisma Zh.Eksp.Teor.Fiz.* **77**, 439 (2003) (*JETP Lett.* **77**, 371 (2003)).

[11] D. S. Golubovic and V. V. Moshchalkov, will be published in *Appl. Phys. Lett.*, available at cond-mat/0509332.